Design and experimental validation of irradiation-resistant temperature-sensitive fiber optic cable for fire detection in activated carbon iodine adsorbers

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Abstract

In order to develop a temperature-sensitive fiber optic cable suitable for fire detection of activated carbon iodine adsorber, this paper proposes a design method for an irradiation-resistant and high-temperature-resistant linear temperature-sensitive fiber optic cable. Through the use of PCVD combined with stepwise doping technology to prepare quartz fibers with a low-fluorine-doped core and high-fluorine-doped cladding, the radiation resistance of the fibers is improved, and the bending resistance is enhanced by incorporating a sunken cladding design. The temperature resistance and mechanical properties of the optical fiber are improved by using a polyimide organic coating layer. Metallized armored fiber optic cabling technology is employed to improve the mechanical properties and anti-aging properties of the organic coating, thereby ensuring the long-term reliability of the radiation-resistant and temperature-sensitive optical cable. Under 10kGy cumulative irradiation, the additional loss of the sample is 3.6dB/km. The maximum loss change is 0.727dB/km during the 280℃ high-temperature resistance test. The temperature detection accuracy is ±7℃ in the range of -20-280℃, which satisfies the technical requirements of activated carbon iodine adsorber fire detection.

Full Text

Design and Experimental Validation of an Irradiation-Resistant Temperature-Sensitive Fiber Optic Cable for Fire Detection in Activated Carbon Iodine Adsorbers

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Abstract: This paper proposes a design methodology for an irradiation-resistant and high-temperature-resistant linear temperature-sensitive fiber optic cable suitable for fire detection in activated carbon iodine adsorbers. The design employs PCVD combined with stepwise doping technology to fabricate quartz fibers with a low-fluorine-doped core and high-fluorine-doped cladding, thereby enhancing radiation resistance. A depressed cladding design is incorporated to improve bending resistance, while a polyimide organic coating layer enhances temperature and mechanical performance. Metallized armored fiber cabling technology further improves mechanical properties and anti-aging characteristics, ensuring long-term reliability of the radiation-resistant temperature-sensitive cable. Under a cumulative irradiation of 10 kGy, the sample exhibits an additional loss of only 3.6 dB/km, with a maximum loss variation of 0.727 dB/km during the 280°C high-temperature resistance test. The temperature detection accuracy is ±7°C across the range of -20°C to 280°C, satisfying the technical requirements for fire detection in activated carbon iodine adsorbers.

1. Introduction

Nuclear air and gas purification systems are essential for protecting the public and plant operators from airborne radioactive particles and gases. Radioactive iodine is of particular concern in these systems, as the human thyroid gland has a high capacity for iodine absorption, making it a significant potential radiation hazard. Activated carbon iodine adsorbers represent the most commonly employed method for removing radioiodine from air and gas streams in nuclear ventilation and purification systems [1].

The adsorption process in activated carbon generates substantial heat, and polymerization, oxidation, and coking reactions can occur within the adsorption unit, creating a risk of spontaneous combustion and fire [2,3]. To accurately detect fire hazards in adsorbers, activated carbon iodine adsorbers require a linear temperature-sensitive fire detection system that can operate reliably in a nuclear radiation environment. The system must accurately and reliably detect temperature and fire location under irradiation. The specific requirements for activated carbon iodine adsorber fire detection are: (1) it must not introduce additional safety hazards such as fire; (2) it must remain functional after absorbing the 60-year cumulative dose; (3) it must be capable of issuing high-temperature alarm signals and withstand temperatures up to 280°C; and (4) it must accurately and rapidly detect fire location.

Existing iodine adsorber fire detectors can meet standard requirements [5,6], but further improvements are possible. Current detectors are typically positioned far from the activated carbon iodine adsorber, generally arranged upstream and downstream of air-handling units rather than in close proximity to the adsorber itself. Additionally, detectors placed near activated carbon utilize special alloy temperature-sensitive cables at high cost. Furthermore, transmitting temperature information through electrical signals via temperature-sensing cables may pose fire risks.

To enhance safety and reduce costs, temperature-sensing optical cables can serve as fire detectors with several advantages: (1) **High safety**: Optical fibers offer inherent safety and reliability, complete electrical insulation, resistance to high voltage and current surges, lightning and explosion protection. Temperature information is transmitted via optical signals without electromagnetic interference or fire risk; (2) **Low cost**: Compared to special alloy temperature-sensing cables, optical cables cost less than one-tenth as much, significantly reducing expenses; (3) **Proximity deployment**: Optical cables can be installed near activated carbon to promptly sense temperature changes and rapidly transmit optical signals to the detection host. The system' s laser emitter can generate tens of thousands of light pulses per second, outputting averaged temperature values to the display system and effectively eliminating errors; (4) **Precise localization**: Temperature-sensing optical cables enable distributed temperature measurement along the fiber length, allowing accurate identification of temperature anomalies and specific fire risk points; and (5) **Long lifespan**: Quartz glass fibers are non-corrosive, fire-resistant, and water-resistant, requiring no maintenance [7,8].

However, applying temperature-sensing optical cables in activated carbon iodine adsorbers requires addressing two key challenges: (1) **Radiation-resistant materials**: High-energy radiation increases optical fiber losses, with higher intensities causing faster, sometimes irreversible, loss increases. To satisfy total reflection requirements, aluminum, phosphorus, and germanium are commonly doped into optical fibers, but these elements degrade radiation resistance. Traditional radiation-hardening methods using cerium doping can cause issues such as increased numerical aperture (NA) and decreased transverse mode instability (TMI) threshold; and (2) **High-temperature treatment**: Under intense heat, organic fiber coatings are prone to aging, yellowing, embrittlement, and delamination, reducing mechanical properties [10-15].

To further improve alarm timeliness and safety of radiation-resistant and high-temperature-sensitive optical cable fire detectors for activated carbon iodine adsorbers, this paper proposes a design methodology for such cables and conducts verification tests on their radiation resistance, high-temperature resistance, and temperature measurement accuracy.

2. Design of Irradiation-Resistant and High-Temperature-Sensitive Fiber Optic Cable

Temperature-sensitive fiber optic cable detection is based on Raman scattering and optical time-domain reflectometry (OTDR) principles, forming a distributed temperature measurement system. Laser energy transmitted through the fiber generates backscattering. When laser pulses of specific energy and width are injected, they continuously produce back Raman scattering—comprising anti-Stokes and Stokes light—while propagating. The intensity of backscattered anti-Stokes and Stokes light is affected by temperature at the scattering point. By demodulating the anti-Stokes intensity and combining OTDR positioning principles, a Raman-type distributed fiber temperature measurement system is realized.

To satisfy optical waveguide total reflection requirements, the core refractive index must exceed the cladding refractive index. Doping with Al O (>0.5 mol%), P O , and GeO increases quartz glass refractive index, while F and SiF doping decreases it. At 1064 nm, 1 mol% GeO doping increases quartz glass refractive index by approximately 19×10 , while 1 mol% P O doping increases it by approximately 50×10 .

To meet radiation resistance requirements, doping element and impurity content in the fiber core and cladding must be optimized. Under identical irradiation conditions, Al-doped quartz fiber exhibits the worst radiation resistance, while pure quartz core fiber shows the best. Ge-doped and P-doped quartz fibers fall between these extremes. Numerous studies demonstrate that doping small amounts of fluorine into the fiber core significantly improves radiation resistance. Therefore, this design employs a low-fluorine-doped core with high-fluorine-doped cladding.

In chlorine-free fibers, higher OH content reduces radiation-induced background loss at 0.9 microns. However, OH exhibits strong absorption at 0.95/1.38/2.2/2.7 m bands. Since this design' s operating band is set at 1.5 m, to avoid OH absorption loss, the scheme utilizes quartz fiber with no chlorine or OH in the core.

To satisfy temperature resistance requirements, the fiber coating must use high-temperature materials. For 280°C operation, only polyimide polymers or metallic aluminum coatings are viable options. However, metallic aluminum coatings are prone to delamination under long-term complete conditions, degrading mechanical and sensing performance. Therefore, polyimide is the optimal coating material for this design.

In practical applications, optical fibers inevitably experience bending, causing increased additional loss, degraded transmission performance, reduced mechanical properties, and shortened service life. To minimize bending-induced loss, this design adopts a depressed cladding configuration. To improve mechanical properties, a fiber cabling design is implemented.

The radiation-resistant temperature-sensitive cable employs preform deuterium pretreatment to eliminate pre-existing color center defects and reduce background loss. Preform pre-irradiation and thermal annealing pretreatment eliminate color center precursors, further enhancing radiation resistance.

To further improve environmental resistance (bending, compression, etc.), a fiber-optic cable design is adopted. The main structure of the irradiation-resistant temperature-sensitive fiber optic cable, from innermost to outermost, comprises: tight-buffered optical fiber, spiral armored tube, and stainless steel braided layer. Structural schematics are shown in Figures 1 and 2, with specific dimensions in Table 1 .

Figure 1. Main structure of irradiation-resistant and high-temperature-resistant temperature-sensitive fiber-optic cable

Figure 2. Sample of irradiation-resistant and high-temperature-resistant temperature-sensitive fiber-optic cable

Table 1. Structural dimensions of irradiation-resistant and high-temperature-sensitive fiber-optic cables

Component	Quantity/Size
Core number (of a fiber)	1
Optical fiber core diameter	50±2.5 μm
Cladding diameter	125±1 μm
Coating layer diameter	245±10 μm
Concentricity error	1.5 μm
Spiral armored tube material	304 stainless steel
Spiral armored tube inner diameter	1.2±0.1 mm
Spiral armored tube external diameter	1.7±0.1 mm
Stainless steel braided layer external diameter	1.7±0.1 mm

3. Irradiation Resistance Test

The radiation-resistant linear temperature-sensing optical cable is deployed in the inlet and outlet flow channels of activated carbon iodine adsorbers. It must remain functional with additional loss less than 20 dB/km after absorbing the 60-year cumulative dose of 10 kGy radiation.

The cobalt source for irradiation testing is a double-grate source equipped with elevation, safety protection, and dosimetry systems. The installed source capacity is 300,000 curies (1.11×10^{1} Bq), with current source intensity of approximately 148,000 curies. The irradiation dosimetry system uses a silver dichromate dosimeter [Ag Cr O working dosimeter with 0.4–5 kGy range], with an L6 UV-Vis spectrophotometer for readout. Dosimetry system error is within 1.2%.

Loss testing equipment is a DTS host with center wavelength 1550 nm, Stokes signal wavelength 1663 nm, and anti-Stokes signal wavelength 1450 nm. The Stokes signal calculates return loss, with results representing the sum of 1550 nm (forward) and 1663 nm (return) losses.

The irradiation-resistant and high-temperature-resistant fiber optic cable test sample is 50 meters long, arranged in the cobalt source room to receive gamma radiation. Testing employs static irradiation mode at 100 Gy/h dose rate, delivering 10 kGy cumulative dose over 100 hours.

Test procedures are as follows: (1) After positioning the test frame and sample in the radiation field, conduct online commissioning, perform basic functional tests and appearance/structure inspections, and record results; (2) Initiate the irradiation resistance test with the specimen in powered operation throughout, monitored in real-time by an online monitoring device. To ensure test continuity and integrity, premature specimen failure terminates the test, recording failure time and cumulative dose. Failure to meet time and dose requirements constitutes test failure; (3) At test conclusion, record irradiation time, perform basic functional tests and appearance/structure inspections, and record results to determine compliance.

Test results are shown in Figure 3 [Figure 3: see original paper], presenting Stokes curves along the cable before irradiation, at irradiation end, and after 24-hour annealing. Irradiation causes additional loss in the fiber optic cable, with slight recovery after 24-hour annealing.

Figure 3. Stokes curves along the cable before irradiation, at irradiation end, and after 24-hour annealing

Figure 4 [Figure 4: see original paper] compares additional loss curves in the irradiated area before irradiation, at irradiation end, and after 24-hour annealing. Approximately 0.27 dB additional loss accumulated over 50 meters at irradiation end, recovering to about 0.2 dB after 24-hour annealing.

Figure 4. Additional loss curves of the tested cable before irradiation, at irradiation end, and after 24-hour annealing

Figure 5 [Figure 5: see original paper] shows irradiation-induced additional loss, which increases with accumulated dose, reaching approximately 6 dB/km at 10 kGy cumulative dose.

Figure 5. Additional loss versus accumulated irradiation dose

Figure 6 [Figure 6: see original paper] illustrates additional loss changes during annealing, showing decreasing loss with increasing annealing time, particularly dramatic at the beginning, stabilizing after 100 hours.

Figure 6. Additional loss changes during annealing

These irradiation tests demonstrate that 10 kGy cumulative irradiation has minimal effect on temperature measurement performance. The temperature measurement function remained operational, with sample additional loss of 6 dB/km well below the 20 dB/km performance requirement.

4. High-Temperature Resistance Test

To achieve high-temperature detection, high-temperature alarm, and high-high alarm signals for temperature-sensing optical cables in activated carbon iodine adsorbers, the cable must withstand 280°C and provide repeatable alarms after temperature recovery to meet regular testing requirements. This article designs a high-temperature resistance test requiring the cable to be heated to 280°C for 8 hours, cooled to room temperature, and reheated. After five such cycles, the temperature measurement performance must remain usable with loss less than 20 dB/km.

Test equipment includes a temperature control chamber (50°C–500°C range), platinum resistance temperature collector (-20°C–300°C range), and optical time-domain reflectometer (OTDR). The test procedure involves loosely coiling the high-temperature-resistant optical cable into a 30 cm diameter fiber coil and placing it in the high-temperature test chamber. One cable end is led out through the chamber outlet. To ensure stable and accurate OTDR data, the cable is directly fusion-spliced with the same type of bare fiber to extend test length, with the other bare fiber end connected to the OTDR for attenuation testing. Simultaneously, a platinum resistance temperature detector is placed in the temperature control box as a standard temperature source. Figure 7 [Figure 7: see original paper] shows the high-temperature loss test rig.

Figure 7. Loss test system under high-temperature condition

First, the OTDR records the attenuation curve and value at 850 nm and 1300 nm wavelengths at room temperature. The temperature control box is then set to 280°C for 8 hours, with attenuation curves and values recorded every two hours. After the high-temperature test, the chamber naturally cools to room temperature and the cable attenuation curve and value are recorded. The high-temperature test cycle repeats for five days.

Additional loss at 850 nm and 1300 nm wavelengths is presented in Figures 8 and 9 [Figure 9: see original paper], respectively. The 1300 nm wavelength shows less additional loss than 850 nm. Additional loss does not increase with heating time. The offset from initial additional loss is shown in Figures 10 and 11, respectively, demonstrating random positive or negative variation within 0.1 dB/km, indicating minimal high-temperature effect on additional loss.

These high-temperature resistance tests demonstrate that 280°C has minimal effect on temperature measurement performance. The temperature measurement function remained operational, with sample additional loss of 3 dB/km well below the 20 dB/km performance requirement.

Figure 8. Additional loss at 850 nm wavelength
Figure 9. Additional loss at 1300 nm wavelength
Figure 10. Additional loss offset from initial additional loss
Figure 11. Additional loss offset from initial additional loss

5. Temperature Measurement Accuracy Test

To verify that the temperature-sensing fiber optic cable can detect activated carbon temperature within -20°C to 280°C range with ±10°C accuracy, a temperature measurement accuracy test was conducted.

Test equipment includes temperature test chambers, high-temperature oil bath, platinum resistance temperature collector, and distributed fiber optic temperature measurement system (DTS). The high-low temperature test chamber adjusts from -20°C to 100°C with ±2°C accuracy. The platinum resistance collector measures -20°C to 300°C with ±2°C accuracy. The high-temperature oil bath ranges from 50°C to 300°C with ±2°C accuracy. The temperature test chamber is used for -20°C to 100°C conditions, while the oil bath is used for 100°C to 300°C conditions.

The high-temperature-resistant fiber optic cable is loosely wound into a 30 cm diameter coil and placed in the test chamber. One cable end is led out through the top exit. To ensure stable and accurate test data, the high-temperature cable is fusion-spliced with the same type of bare fiber to extend test length, with the other bare fiber end connected to the DTS demodulator. The test chamber serves as a standard temperature source. Figure 12 [Figure 12: see original paper] shows the temperature measurement test system.

Figure 12. Temperature measurement accuracy test system for fiber optic cable

During testing, the DTS demodulator is first activated. The high-temperature test chamber is set to 50°C, and temperature correction is performed for the fiber optic cable after platinum resistance temperature stabilization. The test chamber is then set to each test temperature condition. After platinum resistance temperature stabilization, the DTS-displayed temperature value, temperature curve, and platinum resistance temperature value are recorded. Finally, the high-temperature test chamber is turned off and DTS temperature data is exported. The deviation between DTS-displayed temperature and platinum resistance standard temperature is presented in Figure 13 [Figure 13: see original paper].

Figure 13. Measurement deviation of the high-temperature-resistant fiber optic cable

Test results demonstrate that the radiation-resistant and high-temperature-resistant optical cable achieves ±5°C temperature accuracy within the -20°C to 280°C range, meeting the ±10°C accuracy requirement.

6. Layout of the Radiation-Resistant Temperature-Sensitive Fiber Optic Cable in Activated Carbon Iodine Adsorbers

The temperature-sensing optical cable is arranged in a serpentine pattern across the inlet and outlet flow channel cross-sections, as shown in Figure 14. This arrangement enables temperature detection in each inlet and outlet channel, effectively monitoring fire risk. The temperature-sensing optical cable can be installed near activated carbon to promptly sense temperature changes and rapidly transmit optical signals to the detection host. Its distributed temperature measurement capability allows accurate localization of temperature anomalies and specific fire risk points.

(a) Airflow direction
(b) Cross section
Figure 14. Layout of the radiation-resistant temperature-sensitive fiber optic cable in activated carbon iodine adsorber

7. Conclusion

1. Irradiation-resistant temperature-sensitive fiber optic cables are innovatively fabricated using PCVD combined with stepwise doping technology, enhancing radiation resistance through low-fluorine-doped cores and high-fluorine-doped quartz fiber cladding. Bending resistance is improved by employing a depressed cladding design.

2. The radiation-resistant and temperature-sensitive optical cable utilizes polyimide organic coating to improve temperature resistance and mechanical properties. Metallized armored fiber cabling technology enhances mechanical properties and aging resistance of the organic coating, ensuring long-term reliability.

3. The cable employs preform deuterium pretreatment to eliminate pre-existing color center defects and reduce background loss. Preform pre-irradiation and thermal annealing pretreatment eliminate color center precursors, further improving radiation resistance.

4. The designed radiation-resistant and high-temperature-resistant optical cable has passed irradiation resistance, high-temperature resistance, and temperature measurement accuracy tests. Testing shows that 10 kGy cumulative irradiation has minimal effect on temperature measurement performance, with the temperature measurement function remaining operational. Sample additional loss of 6 dB/km meets the requirement of less than 20 dB/km. In high-temperature resistance testing, overall cable attenuation remains relatively stable with minimal variation before, during, and after high-temperature exposure. Maximum attenuation change is 3 dB/km at 850 nm wavelength and 2 dB/km at 1300 nm wavelength, meeting the less than 20 dB/km requirement. In temperature measurement accuracy testing, temperature accuracy is ±7°C across the -20°C to 280°C range, meeting the ±10°C requirement.

In summary, the radiation-resistant and high-temperature-sensitive optical cable proposed in this article meets the temperature measurement requirements for fire detection in activated carbon iodine adsorbers and satisfies performance requirements for irradiation and high-temperature environments. It offers advantages of rapid detection response, high safety, and low cost, making it suitable for fire detection in activated carbon iodine adsorbers.

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Note: Figure translations are in progress. See original paper for figures.